Automation Middleware and Algorithms for Robotic Underwater Sensor Networks

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LONG-TERM GOALS

The long term goals of the project are: (1) To establish systems and algorithms for controlled Lagrangian particle tracking that will be used to improve the accuracy of model based prediction of trajectories of controlled underwater vehicles subjected to ocean current. (2) To achieve a mission planning system for robotic underwater sensor networks that are able to perform automatic or semi-automatic adaptation to extreme ocean conditions and platform failure, deployment, and recovery.

OBJECTIVES

We develop a set of automation middleware that implement a set of novel algorithms for robotic underwater sensor networks serving applications of ocean sampling and ocean model improvement. We design novel model adjustment, cooperative control, and distributed sensing algorithms that will be implemented through the automation middleware. The technical objectives include the following:

1. To investigate a new data assimulation procedure---the controlled Lagrangian particle tracking (CLPT)---and its ability to provide feedback adjustments on ocean modelling systems. To design a validation and adjustment algorithm for ocean models based on CLPT.
2. To develop an automatic middleware that integrates ocean models, robot models, and vehicle control systems towards more accurate prediction of the controlled trajectories of robots in the ocean.
3. To investigate cooperative filters and their ability to improve data quality collected by robotic underwater sensor networks.
4. To design automatic mission planning algorithms for missions with multiple objectives and multiple resolutions. To design a set of efficient and effective control and navigation algorithms that utilize ocean flow to increase mobility with guaranteed sampling performance.
5. To develop a mission planning and optimization system that automatically generates control laws and mission definitions based on user input about mission goals and constraints.

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APPROACH

The work is performed by PI Fumin Zhang and four graduate students: Justin Shapiro who entered Georgia Tech in fall 2008, Wencen Wu who entered Georgia Tech in Spring 2009, Dongsik Chang who entered Georgia Tech in Fall 2009, and Klementyna Szwaykowska who entered Georgia Tech on a NSF graduate fellowship in Fall 2007. In addition, six undergraduate students are hired on an hourly base to develop experimental underwater vehicles. The PI leads the team. Justin Shapiro focuses on system development and also leads the undergraduate students to develop test-bed that includes underwater vehicles. Wencen Wu focuses on cooperative filtering and autonomy algorithms for three dimensional cooperative exploration. Dongsik Chang focuses on systems development and systems reliability. Klementyna Szwaykowska focuses on the CLPT theory, model reanalysis, and path planning algorithms for underwater platforms.

The approach and methodologies employed, corresponding to the above objectives, are as follows:

1. We define the CLPT error as the difference between the predicted trajectories of the robots through simulations using ocean predictions and the actual trajectories of the robots through real ocean experiments. This error is averaged across all robots in a network to generate the average CLPT error. The Eulerian flow predictions generated by ocean models can be improved by minimizing the average CLPT error.
2. We develop a middleware system for CLPT to establish an automatic connection between the ocean modeling systems (NCOM, ROMS, HOPS) and the underwater robot control systems (GCCS or an AUV control system such as the MOOS).
3. We develop cooperative filters that provide optimal least square interpolation for ocean data collected along the trajectories of the robots. A rigorous mathematical approach is followed to justfiy the theoretical soundness of the method. A cooperative Kalman filter is developed as an extension to the original Kalman filtering algorthm (Jazwinski 1970; Stengel 1994). We apply the cooperative Kalman filter algorithm to estimate the representation error for data assimilation in three dimensional space. Error associated with such estimation can be minimized by optimizing the shape of the robot cluster and the time step of the estimation.
4. We use the technique of dynamic programming, fast marching, or A* algorithms to generate optimal paths for ocean sampling platforms such as the underwater gliders to overcome strong ocean current that may exceed platform speed.
5. We develop a middleware system named the automatic mission planning and optimization (AMPO) system that establishes an automatic connection between the users and the underwater robot control systems. We develop a testbed that including ROVs and AUVs to test this system.

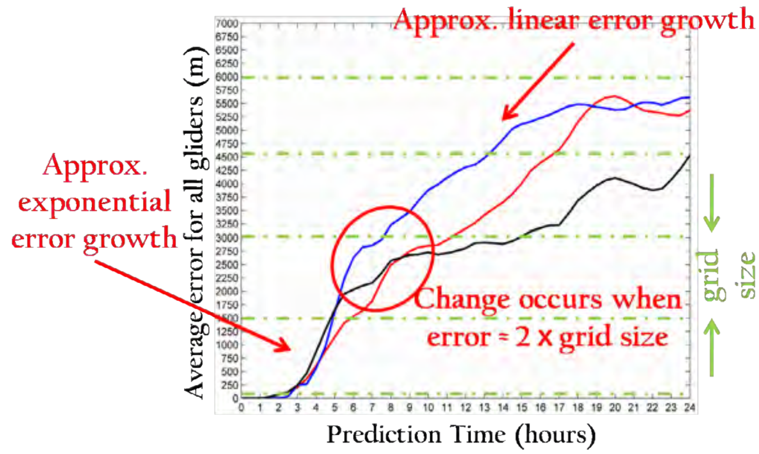


Figure 1. Similar behaviors of the averaged CLPT error across all three ocean models

WORK COMPLETED

Objectives 1 and 2 achieved. Averaged CLPT errors have been computed for ROMS, NCOM, and HOPS ocean models by comparing glider trajectories in the 2006 ASAP experiment in Monterey Bay, CA with recently regenerated ocean predictions. This process is named as model reanalysis. Model reanalysis reports have been generated for different versions of both the NCOM and the ROMS models. Such reports allow ocean modeling teams to test hypothesis made towards improving ocean models, as shown in Figure 1. A rigorous analysis based on the stochastic systems theory has been used to explain the common trend shared by the CLPT error plot of all three models. We have rigorously proved that there exists a lower bound on the steady state CLPT error. Such lower bound is proportional to the grid size of ocean models. Therefore, increasing the spatial resolutions of ocean models will effectively reduce the CLPT error. Our results have been published in two conference papers (Szwaykowska and Zhang 2010, 2011a) with a journal version submitted (Szwaykowska and Zhang, 2011b).

Objective 3 achieved. The cooperative Kalman filtering method has been developed for two dimensional ocean fields. Theoretical results show the method is provably convergent (Zhang and Leonard 2009). A level curve tracking algorithm based on this method has been verified through simulation, see the left figure in Figure 2. We developed autonomy algorithms for mission planning that produces cooperative exploration behaviors under tidal current. See the right figure in Figure 2. Cooperative filtering and cooperative exploration algorithms have been extended to track small features in a three-dimensional field as shown in Figure 3. The number of vehicles have to increase comparing to the two dimensional case, the minimum number of vehicles required have been determined theoretically (Wu and Zhang 2010).

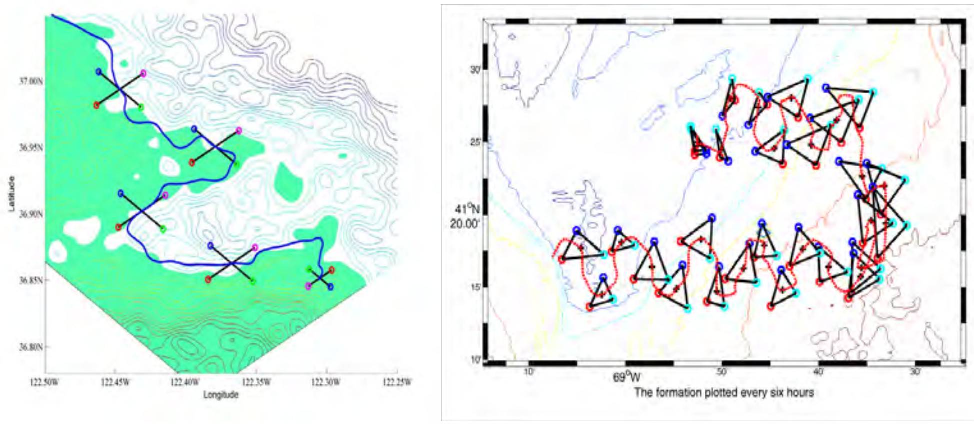


Figure 2. Cooperative exploration behaviors. Snapshots of the robot formation are plotted along the trajectory of the center of the formation. Left: tracking a temperature level curve using four robots. Right: autonomous mission planning under tidal current.

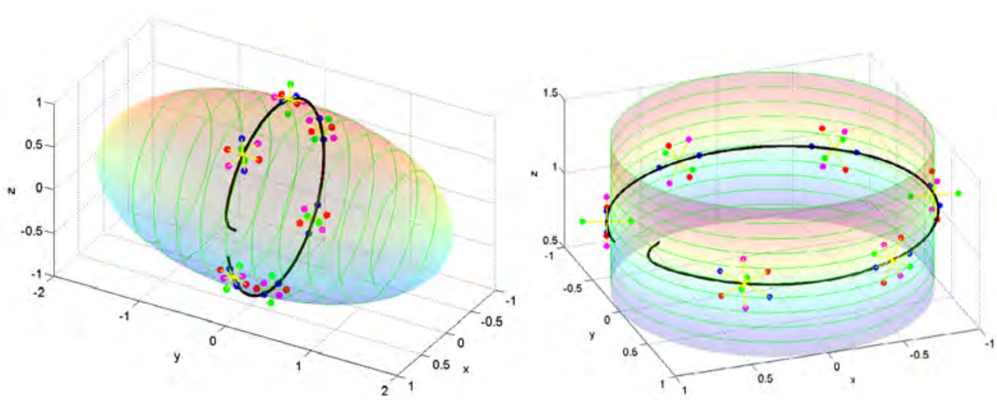
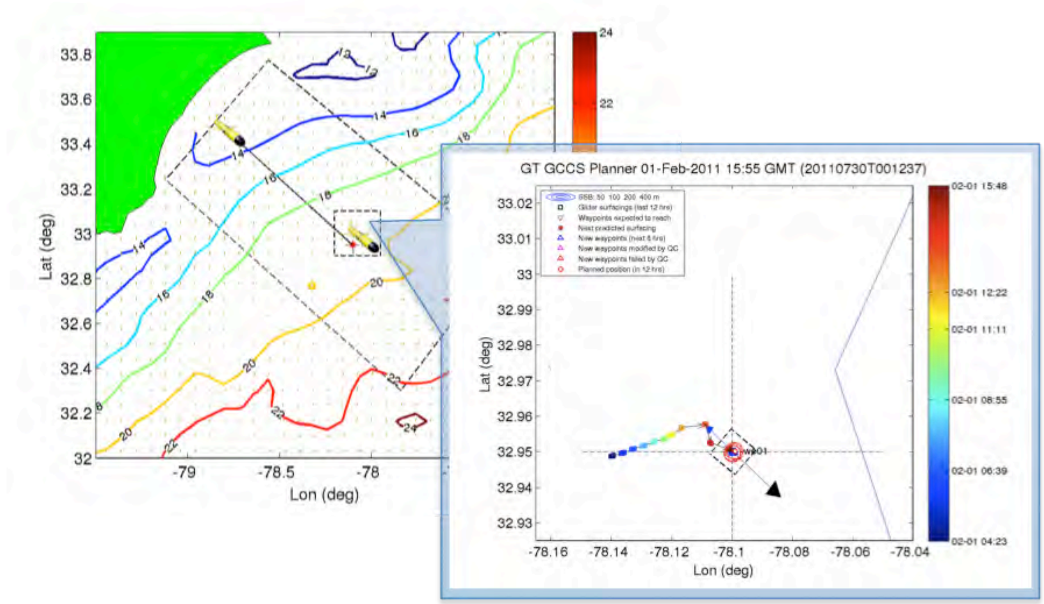


Figure 3. Demonstrations of three dimensional cooperative exploration algorithms.

Objective 4 and 5 achieved. The middleware developed has been implemented as extensions to the Glider Coordinated Control System (GCCS). GCCS has been used to control two underwater gliders in an NSF funded project in Long Bay, SC. Various path planning algorithms have been implemented and tested to allow gliders to hold positions near the gulfstream where flow speed frequently exceeds glider horizontal speed. Figure 4 demonstrate the mission and path planned.



(a) Domain of the Long Bay experiment. Ocean current predicted using HYCOM + NCODA + Simple Tidal Model.

(b) A glider controlled to hold position at (-78.1°, 32.95°). Colored rectangles represent glider surfacing positions with corresponding time in the color bar on the left.

Figure 4. In (a), outer dotted box represents the domain of the Long Bay project, inner dotted box is used for the main focus region for a mooring glider, and the desired position for the mooring is represented as a red dot at (-78.1°, 32.95°). The colored contours represent SST field in the domain, and the arrows covering the entire field show the flow field in the domain. In (b), GCCS generates paths for the glider to hold station under strong current.

As lab based test-bed, we have developed a remotely operative vehicle (ROV) that has won a design excellence award in the 2009 MATE international ROV competition, and won the Martin Klein MATE Mariner Award in 2011. A robot ship is developed and placed 7th in the 4th AUVSI/ONR International RoboBoat Competition.

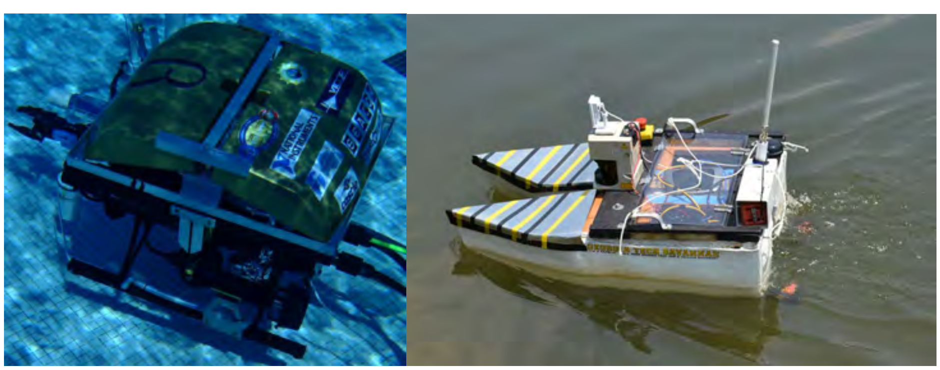


Figure 5. Left: A remotely operated vehicle ROV-Beta developed by PI's undergraduate team. Right: Autonomous Ship Victoria in the 4th AUVSI and ONR International RoboBoat competition.

RESULTS

1. We discovered similar behaviors for all three ocean models regarding the averaged CLPT error in Figure 1. The error first grows exponentially until it reaches twice the grid size. After that, the error grows linearly. By establishing the theory of CLPT, we are able to explain this similarity and generalize this conclusion. We made the discovery that this behavior is unique to controlled Lagrangian particles i.e. marine robots under the guidance of finite resolution ocean models. We also theoretically proved that the bounded error growth is not a repeatable phenomena observed on drifters without active control. Further test and analysis on experimental data are planned in the Long Bay experiment on gliders to confirm our theory.
2. Cooperative filtering and exploration behavior are fundamental building blocks for autonomy of networked unmanned marine systems. Our theoratical developments show that cooperative filtering can be used to explore both 2D and 3D scalar fields.
3. The automation middleware systems have been proved to be effective and convenient in automatic mission planning and path planning for autonomous marine robots. The middelware systems will see contiue usage and wider adoptions in ocean sensing experiments.

IMPACT/APPLICATIONS

The infrastructure we are developing will lead to the fully automated operation of underwater robotic sensor networks that are persistent and intelligent in a constantly changing ocean environment. On top of the operation automation that results in autonomy, the data flow in and out of the autonomy is automated. This impacts not only the gathering of data, but also the assimilation of the gathered data and the improvements of ocean models.

RELATED PROJECTS

The middleware and algorithms are connected with other important research activities of the PI and others around the theme of adaptive sampling using underwater robotic sensor networks.

1. Ocean modeling and glider data assimilation. The middleware design goes hand in hand with the work of the ocean modeling teams from NRL Stennis and NASA JPL. The middleware systems will provide automatic validation and adjustment methods to reduce the CLPT error to improve the accuracy of ocean flow prediction and may be applied to other state variables of the models. Algorithms in estimating the representation error will improve the accuracy of data assimilation.
2. Bio-Inspired Autonomous Control for Optimal Exploration and Exploitation in Marine Environments (BioEx). PI participated in this project sponsored by the ONR. The project goal is to institute an innovative multidisciplinary investigation of autonomous collective foraging in a complex environment that explicitly integrates models and insights from biology with models and provable strategies from control theory. Our methods for autonomy will be rigorously developed and tightly integrated with experimentation
3. Collaborative interface design. Middleware development will benefit from the continuing effort to improve MBARI COOP and other collaboration tools. On the other hand, the functionality of

automatic mission and controller design will shorten the time from when a decision is made to when the decision is implemented.

4. Ocean science missions. The Middleware systems developed have been applied to two recent ocean science missions the PI participates. One mission will deploy underwater gliders in Long Bay, SC to study mechanisms of nutrient input at the shelf margin supporting persistent winter phytoplankton blooms downstream of the Charleston Bump. The other mission uses the robotic platforms the PI developed to survey estuarine area near Louisiana Coast for trace of oil spill.

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PUBLICATIONS

Journal articles:

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HONORS/AWARDS/PRIZES

Recipient: Fumin Zhang
Institution: Georgia Institute of Technology
Award: 2009 NSF CAREER Award
Sponsor: National Science Foundation

Recipient: Georgia Tech Savannah ROV team (Led by Fumin Zhang and Justin Shapiro)
Institution: Georgia Institute of Technology
Award: Design elegance award of the 2009 MATE international ROV competition
Sponsor: Marine Advanced Technology Education (MATE) Center

Recipient: Fumin Zhang
Institution: Georgia Institute of Technology
Award: 2010 ONR YIP Award
Sponsor: Office of Naval Research

Recipient: Fumin Zhang
Institution: Georgia Institute of Technology
Award: 2010 Lockheed Inspirational Young Faculty Award
Sponsor: Lockheed Martin Co.

Recipient: Fumin Zhang
Institution: Georgia Institute of Technology
Award: 2011 Roger P. Webb Outstanding Junior Faculty Award
Sponsor: School of Electrical and Computer Engineering, Georgia Tech

Recipient: Fumin Zhang
Institution: Georgia Institute of Technology
Award: Distinguished Lecturer on Cyber-Systems and Control
Sponsor: Zhejiang University, China

Recipient: Georgia Tech Savannah Robotics (Supervised by Fumin Zhang)
Institution: Georgia Institute of Technology
Award: 2011 Martin Klein MATE Mariner Award
Sponsor: Marine Advanced Technology Education (MATE) Center